Radiation Shielding Materials Recommendations

(Prepared for Code UG by the Radiation Shielding Materials Workshop)

Executive Summary

These recommendations are the result of a workshop held at Lawrence Berkeley National Laboratory, Berkeley, California in August, 2000 to develop a roadmap for the completion of transport code development, recommend research to be solicited in the next NRA and suggest measures for radiation protection on future missions, both in deep space and in low earth orbit. The workshop made specific recommendations for additional nuclear cross sections that need to be measured and used in further transport code development with the goal of calculating specific elemental energy spectra to an accuracy of 25%.

The workshop also recommended validation of the improved transport codes using ground-based as well as space measurements, development of a deep space test bed facility for radiation transport validation as well as testing dosimeters, radiation monitors and other applications and support for materials research aimed at improved radiation shielding materials for ISS and future space missions.

Introduction

Radiation shielding is essential for the protection of astronauts. Radiation shielding materials research is a code UG responsibility. This report contains recommendations for code UG for the direction of the radiation shielding materials research. It is the result of a workshop held at Lawrence Berkeley National Laboratory on the 8th and 9th of August, 2000.

NASA has supported research on radiation protection including the shielding of manned spacecraft for over 30 years. This rich history of important investigations and key discoveries has been summarized in appendix 2. Even this lengthy history does not begin to include all the work on radiation shielding, much of it having been supported by Code S for use in basic cosmic ray research and by DOE, CERN and others for reactor shielding, particle accelerator shielding and other applications.

Charges to the Workshop

1) Recommend a roadmap to bring the radiation transport code development for shielding materials to a successful and fruitful conclusion.
2) Recommend what research should be solicited in the next NRA and what should be solicited by other types of requests for proposals.
3) Suggest some measures as goals for radiation protection on missions in the distant future.

Response to the first charge:

Roadmap for Radiation Transport Code Completion: An essential step towards the solution to the radiation-shielding problem is the development of accurate tools for modeling radiation transport. Considerable progress has been made toward the realization of these tools as described in the historical background section (Appendix 2). We now need a roadmap for the completion of this step in the development of radiation shielding.

The objective of the remaining work is to develop the capability to accurately calculate the radiation environment for IVA and EVA crew scenarios and to develop research goals for integrating improved shielding materials. These materials will be used to optimize the radio-protective properties of future spacecraft and planetary habitats. The workshop recognized the need to define what constitutes completion of this step. It is recognized that radiation health research supported under code UL will develop biologically based risk assessment models. These models will rely on particle energy and charge spectra for the characterization of astronaut's health risks. It is the opinion of this workshop that radiation transport code development will be completed when these codes can calculate the charge and energy spectra resulting from the transport of galactic cosmic radiation though shielding materials to a precision of ±25%. This led the workshop to adopt the following goal:

GOAL: Radiation transport codes must be developed which will determine the spectra to an accuracy of ±25%. This accuracy should be achieved behind typical spacecraft and habitat shielding in the galactic cosmic ray environment. It should be obtained for the spectra of the elements H, He, C, O, Ne, Mg, Al, Si, Ca, Cr, and Fe over the energy range 100 MeV/nuc to 2000 MeV/nuc and neutrons from 0.5 to 1000 MeV.

To achieve this goal, the workshop makes the following recommendations:

1. Use existing cross section data sets to ascertain the accuracy of the present radiation transport models, including HZETRN, HETC, and FLUKA, against the goal stated above.

2. Measure a recommended list of nuclear cross sections (this list of cross sections and the rationale for it is attached as Appendix 1). This should be complemented with work to improve the theoretical estimates of those cross sections that are not measured.

3. Use these new measurements and improved cross section calculations to improve radiation transport codes. Use error propagation techniques to determine which cross sections need to be measured more accurately. Measure additional cross sections if necessary until the goal stated above has been reached.

4. Incorporate measured cross section data into the different radiation transport models currently under development. Establish a feedback mechanism whereby the radiation transport model development community can reprioritize the list of needed cross section measurements following inclusion and evaluation of new cross section data in the different transport codes.

5. Validate that the goal of ±25% precision has been achieved behind typical spacecraft shielding thicknesses. This should be done in two ways: 1) with thick target experiments (These measurements will be done in connection with the cross section measurements recommended above); and 2) in the natural cosmic ray environment using a suite of instruments to measure that environment with and without the shielding.

Once the above-stated goal has been achieved, we recommend two additional steps to bring this step to a fruitful and successful conclusion:

1. Produce a single volume documenting the transport codes developed for manned spacecraft shielding.

2. Provide an archival repository for maintenance and distribution of the transport codes.

The workshop made the following additional recommendations concerning radiation transport code development and implementation as a shielding design tool.

1. Coordinate shielding materials development with GSFC-JPL parts testing program. (Janet Barth).

2. Advocate inclusion of radiation shielding considerations in the initial designs and materials choices for future manned spacecraft.

3. Advocate the inclusion of material compositions in 3-D CAD designs of future manned spacecraft so these data can be ported into the radiation shielding transport tools being developed by code UG.

Response to the second charge:

The workshop discussed the following recommendations responding to the second charge. We recommend three different tasks:

1. Completion of a database consisting of cross section measurements as detailed in Appendix 1 and (for selected targets and beams) measurement of fragment yields in terms of fluence as a function of depth, fragment energy per nucleon and direction of the emitted fragment. This quantity, $\varphi(x,\theta,Z,A,\varepsilon)$, where x is the depth of material, θ is the angle of fragment emission, and Z, A, and ε are, respectively, the fragment charge, atomic mass and energy per nucleon. This is the quantity that transport code calculations will need for comparison in order to be validated; it specifically includes neutrons ($Z=0$, $A=1$).

2. Development of a three-dimensional reference standard code based on a solution to the Boltzmann equation, both as embodied in the current HZETRN code, and as performed by Monte Carlo codes such as FLUKA and HETC where appropriate. For a given set of parameters, validation of these codes is defined as satisfying the condition:

$$\Delta\varphi/\varphi \leq 0.25 \qquad (1)$$

and

$$\Delta\varphi = |\varphi^{*}-\varphi|$$

where φ is the measured particle fluence behind shielding and $\varphi^{*}(x,\theta,Z,A,\varepsilon)$ is the fluence predicted by a given code.

3. Physical validation of the radiation transport codes, based on ground as well as space measurements. This should lead to predictions satisfying the condition stated in equation (1) above for a set of parameters deemed sufficient by NASA.

The workshop recommends that these three tasks be funded in different ways in order to best achieve the perceived NASA goals:

1. A team, functioning in a coherent way over a period of time sufficient to complete the collection of the required measurements best accomplishes data acquisition. Solicitation should be for the formation of such a team, similar to the current NASA Specialized Center for Research and Training

(NSCORT) approach, to deliver specified cross section and yield data on a defined time scale, using the facilities being constructed by NASA at Brookhaven National Laboratory, supplemented as required by others. Two teams may be appropriate: one team to obtain data on charged particles, and one team to obtain data on neutrons. The PI of each team should be a US citizen, although collaborations with foreign investigators are encouraged.

2. Transport code development should also be solicited as a separate NSCORT-type effort.

3. Validation of transport codes should be investigator-initiated, to perform specific experiments, as currently provided by the NRA mechanism.

The workshop recommends supporting materials research that will maximize the radio-protective properties of future spacecraft and planetary habitats. This involves developing and testing materials in both simulated and actual space radiation environments as well as properly accounting for spacecraft and habitat design.

Shielding materials should be non-hazardous and meet the safety requirements for use in manned space flight. Emphasis should be placed on materials that will serve two or more purposes. Materials should be sought that incorporate other desirable properties such structural strength, corrosion resistance, electrical conductivity, etc. that could have specific applications. The shielding effectiveness of proposed materials should be evaluated using HZETRN (see [4]) or the updated transport codes developed in response to these recommendations. Proposed new materials should demonstrate improved shielding effectiveness over polyethylene or other material properties that allow them to be used in applications for which polyethylene is not suitable. In these cases the new material should demonstrate a substantial improvement in radiation shielding effectiveness over the material it replaces. The NRA should also solicit this research.

In addition, Code UG should consider providing a facility for radiation transport code validation and testing of materials, dosimeters, radiation monitors, etc. in the deep space radiation environment. The workshop recommends the development of a balloon-borne test bed flown near the magnetic poles of the earth to access the deep space radiation environment. This test bed is envisioned as a dedicated balloon gondola that can be recovered and re-flown as needed. Such a test bed will provide an economical way to access deep space. This test bed would best be developed jointly with code UL, R and M as a cross enterprise facility.

Response to the third charge:

The workshop discussed innovative or 'out of the box' solutions to radiation protection for manned deep space missions in the distant future. We report here only new ideas not previously discussed.

1. Hydrogen: Hydrogen has long been known to be the ideal radiation shielding material for manned deep space missions. It has been pointed out that a solid hydrogen sphere be protected from the sun in such a way that it would last for several years before sublimating away. Large quantities of liquid hydrogen may be on board as part of the fuel supply for the rocket engines. This hydrogen could, in principle, be used as shielding.

2. Radioprotectants: These are drugs or dietary factors that diminish or ameliorate the harmful effects of space radiation. This is a subject of current research. The radioprotective effects of the drug Tamoxifen are being investigated, as are the effects of diet. It has been suggested that bio-molecular research into the chemical structure of DNA could lead to the development of radioprotectants. Understanding of the chemical processes that lead to radiation-induced cancer expression could perhaps lead to some drug that would bind to damaged DNA in such a way as to inhibit or prevent cancer expression.

3. Recycled Water: Water makes a good radiation shield. The storage for water, recycled water, waste water and food supplies containing water could be arranged to provide crew shielding.

4. EPO: NASA should consider soliciting ideas for radiation shielding for deep space missions as an education and public outreach activity. This would require making public much of the report on Revolutionary Concepts for Radiation Shielding as background.

Appendix 1: Recommended Nuclear Data Requirements for Development of Space Radiation Shielding Materials

Specific data requirements and the rationales for those requirements have been exhaustively examined by several recent studies conducted by NASA [1,2] and, at NASA's behest, by the National Research Council (NRC)[3].

The participants at this workshop concur that particle accelerator measurements of fragmentation of $Z > 1$ nuclei into charged particles and neutrons are needed.

The objectives of the recommended measurements are: (1) to provide reaction cross sections needed as input to radiation transport models, and (2) to determine how close the models are to reaching the goal of ±25% accuracy, by measuring fragmentation in thick elemental and composite targets.

The NRC committee charged to address biological issues concluded, "The knowledge needed to design adequate shielding has both physical and biological components". It defined six "higher priority research questions", one of which is "*How do the selection and design of the space vehicle affect the radiation environment in which the crew has to exist?*" The accompanying text states in part that "For knowledgeable shielding design, the initial radiation fields, the reaction probabilities, and the secondary particles produced as a function of angle must be determined through physical measurements, at a HZE particle accelerator, of the particle types and energies resulting behind different compositions and thicknesses of shielding." Referring to the validation of transport codes, the report goes on to say, "…the transport codes used to calculate the shielding efficiency have to be benchmarked against measured data for elemental and composite shields."

The workshop on neutron production [1] concluded that high-energy secondary neutrons (> 10 MeV) would contribute up to 20% of the total dose equivalent to personnel on the International Space Station. These neutrons will be produced in roughly equal measure by cascades initiated by trapped protons and GCR heavy ions and by GCR projectile fragmentation. For lunar and exploration-class missions, these same effects could produce significant doses from neutrons inside transfer vehicles and planetary habitats.

The workshop on shielding strategies concluded that a number of cross-section and thick target fragmentation measurements are needed, including:

i. energy dependence of the iron fragmentation cross section—^{56}Fe is the heaviest significantly abundant component of the GCR

ii. light ion fragmentation cross sections to elucidate the role of nuclear structure effects—effects to which the models are sensitive, but which can be obscured in the complicated final states of heavy ion interactions

iii. angle dependence of light fragments (including neutrons) produced by proton and heavy ion projectiles (double differential cross section)

iv. fragment yields behind thick targets including polyethylene, H_2O, composites and multiple-layered shielding materials.

v. some effort should be undertaken to obtain complete exclusive cross sections for a few final states to provide benchmarks for event generators used in Monte Carlo transport codes.

Appendix B of Reference 1 contains a matrix of cross sections to be measured. Fig. 1 shows these as data points on a plot of particle type and energy as a function of linear energy transfer (LET). Also shown is the region of maximum relative biological effectiveness (RBE), around an LET value of 100 keV/μm. This region is only sampled sparsely by the data points recommended in Ref. 1 (filled circles), which used physics criteria, more than biological criteria, to arrive at its conclusions. Taking biological criteria into account, the open circles were considered by the present workshop as a less sparse sample of the biologically significant particles and energies (open circles). In addition, since Ref. 1 was published, some progress has been made in filling in the matrix, especially using carbon beams at the heavy ion accelerators in Darmstadt, Germany (GSI) and Chiba, Japan (HIMAC); these data are shown by shading along the carbon LET vs. range curve in Fig. 1. The present workshop reviewed what has been accomplished and what still needs to be done. Some data points were added, in consideration of the need to match physical data with biological effect as a function of energy deposition and to improve understanding of particle production away from the beam axis. The revised matrix is shown in Table I, below. In Table I, ε_p is the energy per particle (in GeV for protons and GeV/nucleon for others), (Z,A) denotes the particle species and the circles correspond to the data of Fig. 1. The X-marks correspond to projectiles and energies where some, but not necessarily a complete set of data points exist (e.g., some targets, some angles).

The targets for which cross sections were required [1] are: C, Al, Cu. To these it is necessary to add water, polyethylene, and new materials resulting from materials research. In addition, for a selected group of targets, particles and energies, angular distributions will be required. In order to have a meaningful measurement this will require data for at least 4 angles.

References

[1] "Shielding Strategies for Human Space Exploration", J.W. Wilson J. Miller, A.Konradi, F.A. Cucinotta, Eds. NASA CP 3360 (1997).

[2] Proceedings of the Workshop: "Predictions and Measurements of Secondary Neutrons in Space", Universities Space Research Association, Center for Advanced Space Studies, Houston, Texas (1998).

[3] "Radiation Hazards to Crews of Interplanetary Missions – Biological Issues and Research Strategies," National Research Council, Task Group on the Biological Effects of Space Radiation. National Academy Press, Washington, DC (1996).

[4] Ram Tripathi has offers to run the HZETRN code for anyone interested in shielding effectiveness evaluations of new materials. He can be contacted at r.k.tripathi@larc.nasa.gov. Private communication (2000)

FIGURE 1: Measurements vs. LET

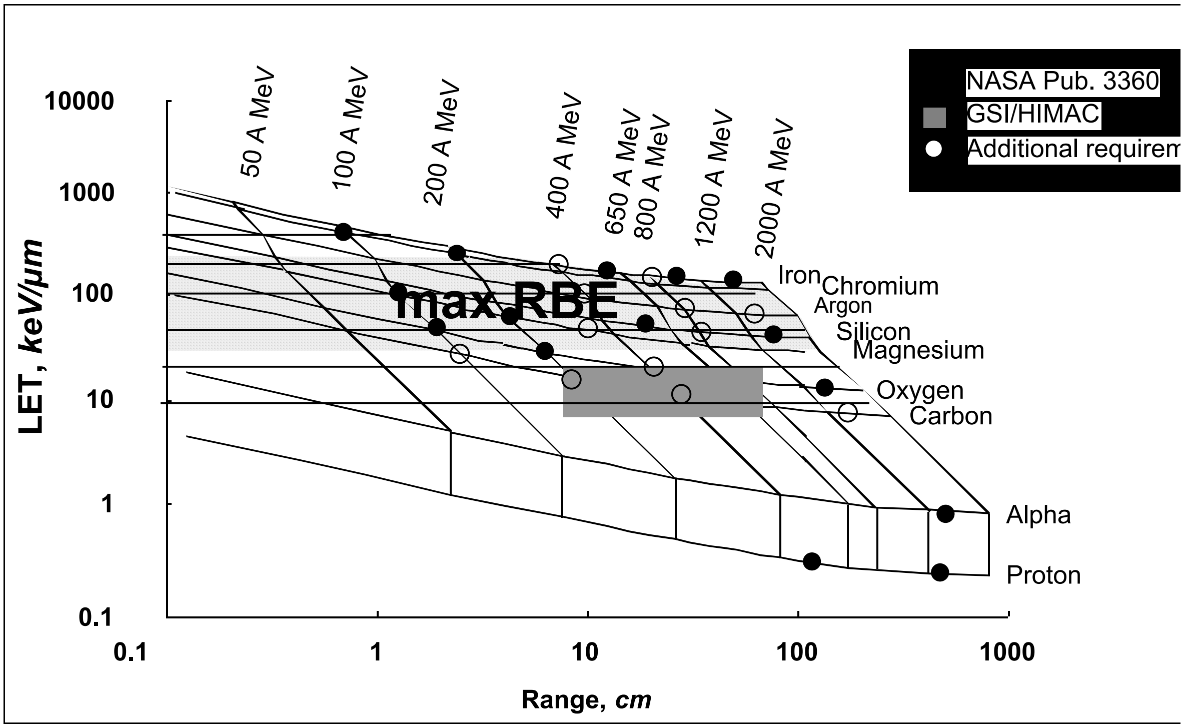

TABLE I

ε_P	(Z,A)										
	H	He	C	N	O	Ne	Si	Ar	Ca	Mn	Fe
0.1		●	❍		●		●				●
0.2	●	●	❍ X	X	●X		●X	X			●X
0.4			❍		❍		❍	❍			❍
0.6		●			●	X	●X				●X
0.8							❍	❍			❍
1.0	●										●X
1.5		●	❍		●		●	❍	●	●?	●
2.0											❍

Appendix 2: Historical Background of Research on Radiation Protection and Radiation Transport though Shielding for this Purpose.

1960s

1. Measurements on Biosattelite 3 that suggested the importance of proton induced target fragments. This was the earliest experimental indication of this issue.

1970s

1. Skylab: first long term flight with significant radiation dose received by crews
2. National Academy of Sciences (NAS) [*National Academy of Sciences,* 1973. HZE Particle Effects in Manned Space flight (D. Grahn, Ed.)] provides first modern definition of radiation problem in space
3. Acceleration of nuclei to relativistic energies at Princeton and Berkeley making possible the simulation of space radiation
4. Projectile fragmentation studies illustrated the importance of heavy ion projectile fragmentation in spacecraft shielding and tissue.
5. Experiments were carried out at the Bevalac using, among other particles, 600MeV/n Fe on a polyethylene target.
6. Large scale animal studies of dose response for tumor induction by fission and fast neutrons show a shallow or flat dose response above a few cGy for many tumor types and a linear dose response for low doses of low LET radiation
7. Development of biological irradiation techniques and dosimetry with HZE particles.
8. Measurements of fragmentation and neutron production by high charge and energy (HZE) ions
9. Relativistic multiple scattering theory of proton-deuteron interactions was successful in describing differential cross sections and polarization [Wilson, J. W. Intermediate energy nucleon-deuteron elastic scattering. Nucl. Phys. B66:221-244; 1973.]
10. Formulation of HZE coupled channel reaction theory and first HZE absorption cross-section database [Wilson, J. W.: Multiple Scattering of Heavy Ions. Glauber Theory, and Optical Model. Phys. Lett., Vol 52B, 1974, p. 149 Wilson, J. W. and Townsend, L. W.: An Optical Model for Composite Particle Scattering. Canadian Journal of Physics, Vol. 59, 1981, p. 1569.]
11. Formulation of an analytical approach to HZE transport theory [Wilson, J.W.; Lamkin, S.L.; "Perturbation approximation to charged particle transport." Nucl. Sci. & Eng. 57:292-299; 1975.]
12. August 4, 1972 solar particle event shown to produce potentially lethal exposures within typical space structures. [Wilson, J. W. and Denn, F. M. Preliminary analysis of Implications of Natural Radiations on Geostationary Operations. NASA TN D-8290, 1976.]
13. Pre-clinical work on cell survival vs. depth, oxygen effects of HZE particles.

1980s

1. Solid tumor data from atomic bomb survivors used to estimate probability of radiogenic cancer

2. National Council of Radiation Protection and Measurements (NCRP) [*National Council of Radiation Protection and Measurements*, 1989. Guidance on radiation received in space activities, NCRP Report No. 98] issues guidelines used as basis for current radiation dose limits for astronauts
3. Use of HZE particles for cancer therapy at the Lawrence Berkeley Laboratory (LBL) BEVALAC; development of high-energy heavy ion physics, including radiation transport properties of shielding and tissue equivalent materials.
4. HZE Relative Biological Effectiveness (RBE) for Harderian gland tumor induction in vivo
5. Abrasion/ablation model based on coupled channel theory successfully applied to HZE fragmentation and first fragmentation cross-section database [Townsend, L. W.; Wilson, J. W.; and Norbury, J. W.: A Simplified Optical Model of Heavy Ion Fragmentation. Canadian J. of Phys. 63 (1), January 1985, pp. 84-101.]
6. HZE space radiation code developed and tested against atmospheric air shower data [Wilson, J. W.; Townsend, L. W.; and Badavi, F. F.: Galactic Cosmic Ray Propagation in Earth's Atmosphere. Radiation Research 109, 1987, pp. 173-183.]
7. Validation of radiation transport for Neon ions, cells in culture at 30-50 percent level
8. In June, 1988, the Robbins report [National Aeronautics and Space Administration Advisory Council. Life Sciences Strategic Planning Study Committee. Frederick C. Robbins, Committee Chairperson. 1988. Exploring the Living Universe: A Strategy for Space Life Sciences. Washington, DC: National Aeronautics and Space Administration] established four challenges to human space flight; one of these was to understand the biological effects of exposure to ionizing radiation.
9. HZE cluster knockout contributions added to abrasion/ablation models. [F. A. Cucinotta; G. S. Khandelwal; L. W. Townsend; and J. W. Wilson: Correlations in A - A Scattering and Semiclassical Optical Models. Physics Lett. B. 223, 1989, p. 127.]

1990s

1. ISS orbital inclination changed from 28° to 51° increasing GCR dose and the threat from Solar Particle Events (SPE)
2. LBL BEVALAC closed (1992) leaving the US without a facility for simulation of GCR HZE particles; this lead to the use of BNL at AGS facility and the start of BAF construction at BNL
3. Results from LDEF experiments conclusively showed the importance of high-LET, short-range target fragments produced in interactions between trapped protons and the mass of the spacecraft. Specifically in LET spectrum measurements by the USF group, a large flux of high-LET particles was found to make a significant (~40%) contribution to dose equivalent. It is important to note that LDEF, in a 28.5° orbit, was shielded from high-LET HZE particles by the geomagnetic cut off. This work was reproduced on the ground in monoenergetic 250 MeV proton beams from Loma Linda.
4. Detailed measurements of space radiation environment, Shuttle/MIR active dosimetry.
5. Materials optimization procedures to control neutron exposures applied to redesign of SAGE-III instrument shield. [Nealy, J.E.; Simonsen, L.C.; Qualls, G.D.; "Modeled

environment and exposures for the SAGE-III instrument configuration." Amer. Nucl. Soc. Topical Meeting: Nuclear Technology for Space Exploration, Proc. Jackson, WY, Aug. 1992.]

6. Development of a compact and portable detector for accelerator-based measurements of nuclear fragmentation and transport [C. J. Zeitlin, K. A. Frankel, W. Gong, L. Heilbronn, E. J. Lampo, R. Leres, J. Miller and W. Schimmerling: A modular solid state detector for measuring high energy heavy ion fragmentation near the beam axis. Rad. Meas. 23, 65 (1994).]
7. Accelerator-based validation of a Monte Carlo model of fragment production and transport based on the NUCFRG2 fragmentation model. Average LET's for fragments produced by iron ions in a polyethylene target are accurately predicted, iron fluences are predicted to 4-8% and fragment yields to better than 10% in most cases. [C. J. Zeitlin, L. Heilbronn, J. Miller, W. Schimmerling, L. W. Townsend, R. K. Tripathi and J. W. Wilson: The fragmentation of 510 AMeV ^{56}Fe in polyethylene. II. Comparisons between data and a model. Radiat. Res. 145, 666 (1996).
8. Measurements of genomic instability, sister chromatid exchanges, gene induction and HPRT mutations demonstrate a weak or flat dose response at low doses of high LET radiation.
9. QMSFRG model elements completed with nuclear cluster knockout processes included. [Cucinotta, F.A.; Wilson, J.W.; Townsend, L.W.; "Abrasion-ablation model for neutron production in heavy ion collisions," Nucl. Phys. A 619:202-212; 1997.]
10. Development and validation of radiation transport calculation methods (HZETRN, QMSFRG); identification of materials of low atomic mass as superior for radiation shielding[Shinn, J.L.; Cucinotta, F.A.; Simonsen, L.C.; Wilson, J.W.; Badavi, F.F.; Badhwar, G.D.; Miller, J.; Zeitlin, C.; Heilbronn, L.; Tripathi, R.K.; Clowdsley, M.S.; Heinbockel, J.H.; Xapsos, M.A.; "Validation of a Comprehensive Space Radiation Transport Code", IEEE Transactions on Nuclear Science, 45(6), Part 1: 2711-2719; 1998.]
11. CNO ion transport at 670 A MeV in water targets calculated to within 15 percent of experimentally measured values [Wilson, J. W.; Cucinotta, F. A.; Tai, H.; Shinn, J. L.; Chun, S. Y.; Tripathi, R. K.; and Sihver, L.: Transport of Light Ions in Matter. Adv. Space Res. 21(12): 1763-1771; 1998]
12. Space flight validation of transport codes on instrumented shuttle flights [Badhwar, G. D.; Patel, J. U.; Cucinotta, F. A.; and Wilson, J. W.: Measurements of the Secondary Particle Energy Spectra in the Space Shuttle. Radiat. Meas., 24: 128-138; 1995.]
13. Design rules for shield materials optimization established. [Wilson, J. W.; Kim, M.; Schimmerling, W.; Badavi, F.F.; Thibeault, S.A.; Cucinotta, F.A.; Shinn, J.L.; Kiefer, R.; "Issues in space radiation protection: Galactic Cosmic Rays," Health Physics 68: 50-58; 1995.]
14. Multifunctional/multidisciplinary optimization procedures proposed based on high-speed radiation analysis procedures as means to reduce mission costs. [Wilson, J.W.; Cucinotta, F.A.; Shinn, J.L.; Kim, M.Y.; Badavi, F.F.; Chapter 1: Preliminary Considerations. Shielding Strategies for Human Space Exploration, NASA CP-3360, p. 1, 1997.

15. NAS/NRC report, “Radiation Hazards To Crews Of Interplanetary Missions: Biological Issues And Research Strategies,” provides basis for estimate of approximately 600 hours of beam time per year required to simulate components of space radiation for acquisition of biological knowledge.
16. In 1998, the Associate Administrator of OLMSA signed the Space Radiation Health Research Strategic Program Plan, which established the phased schedule required to predict risk, reduce uncertainty and develop countermeasures in a manner consistent with the NASA Strategic Plan and external advisory reports.
17. First NASA-sponsored biology and physics experiments at the Brookhaven National Laboratory (BNL) Alternating Gradient Synchrotron (1995). Six sets of HZE experiments were completed by 1999.
18. Construction of the Booster Application Facility (BAF) at BNL was approved in 1999m for a total cost of 33.1M. BAF is expected to become operational in FY02. Operating costs of BAF to deliver 600 hours of beam time/year is expected to be $5M/ year.
19. Fragment production cross sections measured at the BNL AGS resolve a disagreement between previous measurements with iron ions. [C. Zeitlin, L. Heilbronn, J. Miller, S. E. Rademacher, T. Borak, T. R. Carter, K. A. Frankel, W. Schimmerling and C. E. Stronach: Heavy fragment production cross sections from 1.05 GeV/nucleon ^{56}Fe in C, Al, Cu, Pb and CH_2 targets. Phys. Rev. C 56, 388 (1997).]
20. Heavy Ion Medical Accelerator at Chiba (HIMAC), National Institute of Radiological Sciences, Japan made available on a limited basis for physics and biology experiments. NASA-supported physicists and biologists perform experiments at HIMAC (1997-2000), including fragmentation measurements with ions including silicon and iron at energies up to 400 MeV/u.
21. Biological discoveries: cancer susceptibility genes, signal transduction pathways linking cellular communication systems; mechanisms associated with the p53 gene, including apoptosis; modulation of the cell cycle and checkpoints, role of recombination in DNA repair, etc.
22. Materials maximum shielding performance factors established. [Wilson, J.W.; Cucinotta, F.A.; Miller, J.; Shinn, J.L.; Thibeault, S.A.; Singleterry, R.C.; Simonsen, L.C.; Kim, M. H.; “Materials for shielding astronauts from the hazards of space radiations.” Mat. Res. Soc. Symp. Proc. 551:3-16; 1999]
23. Isospin rule violations in medium corrections to nucleon-nucleon amplitudes. [Tripathi, R.K.; Cucinotta, F.A.; Wilson, J.W.; “Medium modified nucleon-nucleon cross sections in a nucleus.” Nucl. Inst. & Meth. B 152: 425-431; 1999]
24. Reverse flux of Mars surface neutrons predicted as shielding issue and MARS 2003 mission science requirements established. [Wilson, J. W.; Kim, M.Y.; Clowdsley, M.S.; Heinbockel, J.H.; Tripathi, R.K.; Singleterry, R.C.; Shinn, J.L.; Suggs, R.; “Mars surface ionizing radiation environment: Need for validation.” Mars 2001: Integrated Science in Preparation for Sample Return and Human Exploration, Lunar and Planetary Institute, Houston, LPI Contribution No. 991, p. 112, 1999.]
25. Space radiation specific multigroup methods established. [Clowdsley, M.S.; Heinbockel, J.H.; Kaneko, H.; Wilson, J.W.; Singleterry, R.L.; Shinn, J.L.; “A

comparison of the multigroup and collocation methods for solving the low-energy neutron Boltzmann equation." Can. J. Phys. 78:45-56; 2000.
26. Advent of inexpensive "super-computer"-like computing power based on desktop PC technology making Monte Carlo techniques from high energy particle physics practical for space radiation simulation
27. Universal parameterization of absorption cross sections[Tripathi, R.K.; Cucinotta, F.A. Wilson, J.W.; NASA TP 3621, 1997]
28. Accurate universal parameterization of absorption cross sections II - neutron absorption cross sections [Tripathi, R.K.; Wilson, J.W.; Cucinotta, F.A.; Nucl. Instr. Meth. Phys. Res. B 129 (1997)
29. New parameterization of absorption cross sections [Tripathi, R.K.; Wilson, J.W.; Cucinotta, F.A.; NASA TP 3635, 1997.]
30. Universal parameterization of absorption cross sections II - Light systems [Tripathi, R.K.; Cucinotta, F.A., Wilson J.W. NASA TP-1999-209726]
31. Accurate universal parameterization of absorption cross section III - Light systems – [Tripathi, R.K.; Cucinotta, F.A.; Wilson, J.W.; Nucl. Instr. Meth. Phys. Res. B 155 (1999) 349-356]

The Space Radiation Health Program has sponsored a number of workshops and working groups in order to better define programmatic goals and directions:

Space Flight Validation of Radiation Risk. January 24-26, 1996. Universities Space Research Association, 3600 Bay Area Boulevard, Houston, TX 77058

Foundations of Solar Particle Event Risk Management Strategies. Findings of the Risk Management Workshop for Solar Particle Events. April 10-12, 1996. ANSER, Suite 800, 1215 Jefferson Davis Hwy., Arlington, VA 22202.

Acceptability of Risk From Radiation - Application to Human Space Flight. April 30, 1997. Symposium Proceedings No. 3. Bethesda, MD: National Council on Radiation Protection and Measurements.

Modeling Human Risk: Cell & Molecular Biology in Context. June, 1997. Ernest Orlando Lawrence Berkeley National Laboratory Report LBNL-40278. Berkeley, CA

Shielding Strategies for Human Space Exploration. J. W. Wilson, J. Miller, A. Konradi and F. A. Cucinotta, Editors. NASA CP-3360, December 1997, pp. 456. Also available from the NASA Langley Technical Reports Server at: http://techreports.larc.nasa.gov/ltrs/ltrs.html

Predictions and Measurements of Secondary Neutrons in Space, Universities Space Research Association, Center for Advanced Space Studies, Houston, Texas (1998).

ACRONYMS

ACCESS	Advanced Cosmic Ray Composition Experiment for Space Station
BAF	Booster Accelerator Facility (Brookhaven National Laboratory)
CERN	European Center for Nuclear Research (Switzerland)
EGS	Electromagnetic and Gamma Simulation
GCR	Galactic Cosmic Rays
GSI	Heavy Ion Accelerator Research Center (Darmstadt, Germany)
HEDS	Human Exploration and Development of Space
HIMAC	Heavy Ion Medical Accelerator Center (Chiba, Japan)
ISS	International Space Station
LEO	Low Earth Orbit
ORNL	Oak Ridge National Laboratory (Oak Ridge, Tennessee)
QMST	Quantum Multiple Scattering Theories
MDO	Multidisciplinary Optimization
PAW	Physics Analysis Work Station
RSICC	Radiation Safety Information Computational Center (ORNL)
RTC	Radiation Transport Code
SCOR	Specialized Center of Research
SEE	Single Event Effects
SEP	Solar Energetic Particles
SLAC	Stanford Linear Accelerator Center (Palo Alto, California)
SPE	Solar Particle Event
SSB	Space Studies Board
TEPC	Tissue Equivalent Proportional Counter
BRYNTRN	Baryon Transport Model
CAD	Computer Assisted Design
CHIME	Cosmic-ray Heavy Ion Micro Electronic Code
FLUKA	Monte Carlo Simulation Code
GEANT	Monte Carlo Simulation Code
HETC	High Energy Transport Code
HZTRN	High Energy Heavy-Ion Transport Code
INFN	Italian National Space Agency
LAHET	Los Alamos High Energy Transport
MACREE	Cosmic Ray Radiation Effects Model
MAPTIS	Materials Database at Marshall Space Flight Center
NOVICE	Cosmic Ray Radiation Effects Model
NUCFRG	Nuclear Fragmentation Model
QMSFRG	Quantum Multiple Scattering Fragmentation Model
ROOT	Data analysis package for use with GEANT or FLUKA